CHAPTER 3

HYDRODYNAMIC ANALYSIS OF ESTUARIES

Section I. Factors Influencing Hydrodynamics

3-1. Introduction. A hydrodynamic analysis of a complex estuarine system requires a reasonable knowledge of those factors influencing estuarine circulation. Circulation in estuaries is quite complex and mainly dependent on the relative magnitudes of tidal variations in water levels and currents, freshwater inflow, gravitational forces caused by density differences between the ocean and fresh water, and to a lesser extent, the Coriolis acceleration. Wind and waves also become important for some estuaries and for short durations in most estuaries. The mixing regime and resultant salinity distribution depend on the relative magnitudes of these forces.

3-2. Tides. See Paragraphs 2-11 through 2-19.

3-3. Freshwater Inflow. See Paragraphs 2-25 and 2-26.

3-4. Salinity. See Paragraphs 2-5 through 2-9.

3-5. Coriolis Force. In large estuaries the earth's rotation deflects flowing water to the right in the northern hemisphere and to the left in the southern hemisphere. In the northern hemisphere, flood tide currents are deflected towards the left (looking seaward) and ebb current to the right, resulting in a net counterclockwise circulation. This circulation is referred to as Coriolis circulation. Therefore, water-surface elevations are higher on the left (looking seaward) during flood tide and higher on the right during ebb tide. Coriolis force explains why in Chesapeake Bay the salinity is, on the average, higher on the eastern shore (on the left looking seaward) than on the western shore. A detailed discussion on Coriolis is given by Officer (1976).

3-6. Geometric Influences. The amplitude of a tidal wave progressing up an estuary is influenced by the geometry of the estuary in several ways:

a. If the estuary is convergent, the amplitude tends to increase.

b. Since the length of the estuary is generally less than the tidal wavelength, wave reflection from the sidewalls may be expected due to rapid convergence. This continuous reflection of energy tends to reduce the incident wave amplitude.

c. Energy dissipation by boundary friction tends to reduce the amplitude of the incident wave. If the estuary has a small bottom slope and is very long and without physical obstructions, the latter two effects may dominate and the tidal amplitude may gradually diminish to zero. The motion in such an estuary is therefore characterized by a single progressive wave. In such case the incident wave at the ocean entrance is equal to that which would be observed by a tide gage at that point.

3-7. Seiching. Seiches are standing waves of relative long periods that occur in basins. Seiches in basins within estuaries can be generated by local changes in atmospheric pressure and wind and by oscillations transmitted into an estuary from the open sea. Standing waves of large amplitude are likely to be generated if the force that sets the water basin in motion is periodic in character, especially if the period of the force is the same as, or is in resonance with, the natural free oscillating period of the basin. Equations that can be used to evaluate basins with regard to seiching problems have been developed (Abbot 1979 and Silvester 1974).

3-8. Temperature. The density of seawater depends on both the salinity and temperature, but in estuaries the salinity range is large and the temperature range is generally small. Consequently, temperature has a relatively small influence on the density. Little information has been published on temperature fluctuations in estuaries. One can visualize estuaries, however, where temperature could be a dominant factor at times. Many tropical estuaries have little riverflow entering them during the hot season. Surface heating could then provide sufficient density difference between the estuary and the sea to maintain a gravitational circulation; however, these effects would be transitory. In many fjords there is no river discharge in winter and surface waters can then become more dense than those at depth and will tend to sink. This vertical circulation phenomenon is known as thermocline convection.

Section II. Solution Methods

3-9. General. Solutions to estuarine hydrodynamic problems are obtained principally by use of the four primary methods--field observations, analytical solutions, numerical models, and physical models. Any of these four, or a combination thereof, may be the best approach for solving a particular problem. Choosing between them requires knowledge of the phenomena that are important to the problem and an understanding of the strengths and weaknesses of the solution methods (McAnally et al. 1983).

3-10. Field Observations. Field (prototype) data collection and analysis serve both as an important aspect of the other solution methods and as an independent method. Alone, field data demonstrate the estuary’s behavior under the specific set of conditions that existed during the time of measurement. By skillful scheduling of data collection, careful analysis, and luck, one can obtain estimates of the separate effects of tides, river discharge, wind, and other variables. Field data can reveal problem areas, define the magnitude of problems, and can, to a limited extent, be used to estimate the estuary’s response to different conditions of tide and river discharge. They can also be used in an attempt to identify changes caused by a modification to the estuary. Field data are also an indispensable element in verification of numerical and physical models; they are used by the modeler to adjust the model and show that model results are reliable. Obtaining sufficient temporal and spatial data coverage in the field is a formidable and expensive task; available field data are often too sparse to describe an estuary in any but the most general terms. Those not intimately familiar with data collection and analysis often overestimate the accuracy and reliability of the data. Information on the design of a field survey along with an example is given in Appendix B.

3-11. Analytical Solution Methods. Analytical solutions are recognized as a separate solution method, but they must be carefully defined to distinguish them from numerical models. Analytical solutions are those in which answers are obtained by use of mathematical expressions. These expressions or equations describe physical phenomena in mathematical terms and thus may be considered to be mathematical models of physical reality. For example, Manning's equation is a simple analytical model of the complex process of energy losses in open-channel flows. A more rigorous and complete analytical model of the losses is included in the turbulent version of the Navier-Stokes equations, known as the Reynolds equations.

a. Analytical models usually combine complex, poorly understood phenomena into coefficients that are determined empirically. Manning's roughness coefficient, for instance, combines the various effects of energy dissipation into a single parameter. The degree of simplification of the analytical model dictates how it is solved. For example, Manning's equation can be solved directly, whereas the Reynolds equations must be simplified and solved by numerical methods.

b. If an analytical model can be solved by substituting values of the independent variables into the equation (a closed form solution), then the solution method is also analytical. The calculation may be performed by hand or by a computer, but the solution is still an analytical one.

c. The analytical solution method has advantages of speed and simplicity but it cannot provide many details. In estuaries, analytical solutions can be used for gross representations of tidal propagation and average cross-sectional velocities in simple geometries. Details of flow cannot be predicted. The usefulness of analytical solutions declines with increasing complexity of geometry or increasing detail of results desired.

d. As an example, an analytical solution technique for the prediction of salinity intrusion in an estuary is given in Appendix C.

3-12. Numerical Modeling. Numerical modeling employs special computational methods, such as iteration and approximation, to solve mathematical expressions that do not have closed form solutions. A numerical model thus applies numerical (computational) analysis to solve mathematical expressions that describe the physical phenomena. The distinction between analytical solutions obtained by computer calculations and numerical modeling solutions may become blurred, but the distinction is a valid one that should be maintained. In this EM, the computer programs used to solve the governing equations are referred to as generalized computer programs or codes. When the codes are combined with a geometric mesh (grid) and specified parameters representing a particular estuary, the combination is called a model.

a. Numerical models used in coastal hydraulic problems are of two principal types--finite difference and finite element. The finite difference method (FDM) approximates derivatives by differences in the value of variables over finite intervals of space and time. This requires discretization of space and time into regular grids of computation points. Finite difference methods have been in widespread use for unsteady flow problems since 1970, whereas the finite element method (FEM) has been widely applied to open-channel flow problems only since 1975. The latter method employs piecewise approximations of mathematical expressions over a number of discrete elements. The assemblage of piecewise approximations is solved as a set of simultaneous equations to provide answers at points in space (nodes) and time.

b. Numerical models are classified by the number of spatial dimensions over which variables are permitted to change. Thus in a one-dimensional flow model, currents are averaged over two dimensions (usually width and depth) and vary only in one direction (usually longitudinally). Two-dimensional models average variables over one spatial dimension, either over depth (a horizontal model) or width (a vertical model). Three-dimensional models solve equations accounting for variation of the variables in all three spatial dimensions.

c. Numerical modeling provides much more detailed results than analytical methods and may be substantially more accurate, but it does so at the expense of time and money. Models of sufficient detail may require very large computers to solve the large systems of equations and store results. Once a numerical model has been formulated and verified for a given area, it can quickly provide results for different conditions. Numerical models are capable of simulating some processes that cannot be handled in any other way. However, they are limited by the modeler’s ability to provide and accurately solve mathematical expressions that truly represent the physical processes being modeled. For example, existing three-dimensional models are presently considered to be the most effective method for predicting wind-induced currents in complex geometry, but physical models are considered superior for salinity-induced density current prediction in complex geometries. Because of their newness, much less is known about the ability of numerical three-dimensional models to reproduce estuarine flows. An example two-dimensional numerical model investigation is given in Appendix C.

3-13. Physical Models. Physical scale models have been used for the past century to solve estuarine hydraulic problems. Careful observance of appropriate scaling requirements permits the physical modeler to obtain reliable solutions to problems that often can be solved no other way. Physical hydraulic models of estuaries can reproduce tides and other long waves, some aspects of short-period wind waves, longshore currents, freshwater flows, pollutant discharges, some aspects of sedimentation, and three-dimensional variations in currents, salinity, density, and pollutant concentration. Applicability of model laws and choice of model scales are dependent on which of these phenomena are of interest. Present practice does not include simulation of water-surface setup and currents due to wind. Conflicts in similitude requirements for the various phenomena usually force the modeler to neglect similitude of some phenomena to reproduce more accurately the dominant processes of the situation. For example, correct modeling of tides and currents often requires that a model have different scales for vertical and horizontal lengths. This geometric distortion permits accurate reproduction of estuarine flows and is a common and acceptable practice, but it does not permit optimum modeling of short-period waves, which requires an undistorted-scale model for simultaneous reproduction of refraction and diffraction.

3-14. Hybrid Method. The preceding paragraphs have described the four principal solution methods and some of their advantages and disadvantages. In practice, two or more methods are used jointly, with each method being applied to that portion of the problem for which it is best suited. For example, field data are usually used to define the most important processes and verify a model that predicts hydrodynamic conditions in an estuary. Combining two or more methods in simple ways has been common practice for many years. Combining physical modeling and numerical modeling to provide results not obtainable any other way is termed a hybrid solution method; combining them in a closely coupled fashion that permits feedback between the models is termed an integrated hybrid solution. Judicious selection of solution methods in a hybrid approach can greatly improve accuracy and detail of the results. By devising means to combine results from several methods, the modeler can include effects of many phenomena that previously were neglected or poorly modeled. Examples of processes that are good candidates for hybrid modeling are sediment transport and flow hydrodynamics or tidal flows and short-period waves. In the first case, hydrodynamics drives the sediment transport process, and if the study is carefully designed, the feedback from bed change to hydrodynamics is minimal. In the second case, the interaction of the two processes is often dominated by one or the other such that they can be analyzed as independent events and the results combined. Processes that have a strong feedback loop, such as the hydrodynamics of freshwater/saltwater interaction, are not suitable for the hybrid approach and consequently should be analyzed together.